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DEPOLARIZATION AND SCATTERING
OF ELECTROMAGNETIC WAVES

FINAL REPORT

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JUNE 30, 1986

U. S. ARMY RESEARCH OFFICE

CONTRACT/GRANT NUMBER
DAAG29-82-K-0123

UNIVERSITY OF NEBRASKA-LINCOLN

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AR0 18120.17-EL	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Depolarization and Scattering of Electromagnetic Waves		5. TYPE OF REPORT & PERIOD COVERED FINAL May 17, 1982-June 30, 1986
		6. PERFORMING ORG. REPORT NUMBER 8
7. AUTHOR(s) Ezekiel Bahar		8. CONTRACT OR GRANT NUMBER(s) DAAG29-82-K-0123
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Nebraska-Lincoln Electrical Engineering Department, Lincoln NE 68588-0511		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Research Office Post Office Box 12211 Research Triangle Park, NC 27709		12. REPORT DATE June 30, 1986
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) NA		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report) NA		
18. SUPPLEMENTARY NOTES The view, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Depolarization, Scattering, Equation of Transfer, Incoherent Specific Intensities, Stokes Parameters, Full Wave, Physical Optics, Perturbation, Diffuse Scattering, Co-polarized, Cross-polarized, Scattering Cross Sections, Extinction Cross Sections.		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) (see next page)		

Item #20. ABSTRACT

The principal purpose of the research is to investigate radio wave scattering and depolarization by conducting objects of irregular shape. To test the programs and in order to develop better physical interpretations of the results, scatterers with simple shapes are considered first. Thus, the full wave solutions for scattering and depolarization are compared with known solutions to the problem.

The second phase of this work is devoted to the problem of scattering and depolarization by irregularly shaped objects. Both one- and two-dimensional problems are considered. To account for medium losses the scatterer is characterized by a complex permittivity and permeability. Using the full wave approach it is not necessary to employ the approximate impedance boundary conditions.

Special attention is given to determining the normalized co-polarized and cross-polarized backscatter cross section. The full wave solutions for the scattering cross sections are compared with the perturbational and physical optics solutions. Special attention is also given to the polarization dependence of the scattering cross sections. ~~+~~

The third phase of this investigation is devoted to the solution of the equation of transfer for the incoherent specific intensities in a media consisting of random distributions of irregular shaped particles. The random rough surfaces of the particles are characterized by their surface height autocorrelation function. Both single scatter and multiple scatter results are presented.

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1. INTRODUCTION - STATEMENT OF THE PROBLEM

The principal purpose of the research is to investigate radio wave scattering and depolarization by conducting objects of irregular shape. To test the programs and in order to develop better physical interpretations of the results, scatterers with simple shapes are considered first. Thus, the full wave solutions for scattering and depolarization are compared with known solutions to the problem.

The second phase of this work is devoted to the problem of scattering and depolarization by irregularly shaped objects. Both one- and two-dimensional problems are considered. To account for medium losses the scatterer is characterized by a complex permittivity and permeability. Using the full wave approach it is not necessary to employ the approximate impedance boundary conditions.

Special attention is given to determining the normalized co-polarized and cross-polarized backscatter cross section. The full wave solutions for the scattering cross sections are compared with the perturbational and physical optics solutions. Special attention is also given to the polarization dependence of the scattering cross sections.

The third phase of this investigation is devoted to the solution of the equation of transfer for the incoherent specific intensities in a media consisting of random distributions of irregular shaped particles. The random rough surfaces of the particles are characterized by their surface height autocorrelation function. Both single scatter and multiple scatter results are presented.

2. SUMMARY OF RESULTS

Over the period of this contract the principal investigator submitted twenty-one manuscripts for publication in Scientific/Technical Journals, presented seventeen conference papers and submitted seven Semi-Annual Technical Reports. In addition, the research leading to a Ph.D. dissertation was supported by this contract (see Section 6 for a detailed list).

The topics of the publications and conference presentations can be classified into three main groups.

The first group is related to scattering and depolarization by rough surfaces* (1), (4), (5), (6), (8), (11), (12), (14), (18), (24), (27), (28), (30), (31), (33), (34), (35), (38). In this work the full wave approach based on the unified and two-scale models of the rough surfaces is used to determine the co-polarized and cross-polarized scattering cross sections. The full wave solutions which are based on complete expansions of the fields and the imposition of exact boundary conditions are shown to reduce to the physical optics solutions in the high frequency limit and the small perturbation solution in the low frequency limit. Surfaces with Gaussian as well as non-Gaussian surface height probability density functions are considered and the slope probability densities are assumed to be either isotropic and Gaussian or non-isotropic and non-Gaussian. The rough surface is characterized by its

*Reference numbers correspond to list given in Section 6.

surface height spectral density function (the Fourier transform of its autocorrelation function). Using the unified full wave approach, the inadequacy of employing the commonly used hybrid physical optics-perturbation approach to rough surface scattering has been established.

The second group of publications deals with scattering by finitely conducting objects with irregular shapes, such as cylinders and spheres and disks (flakes) with random rough surfaces: (2), (3), (7), (9), (10), (13), (15), (19), (21), (22), (23), (25), (26), (29), (32), (36). The mean square heights of the rough surfaces are assumed to be very large such that the familiar small perturbation approach is not suitable to analyze these problems. The particle rough surface is characterized by different surface height spectral density functions and complex permittivities. Thus, different scales of roughness are considered and the effects of varying the mean square height and the mean square slope (and the related correlation distances) are examined in detail. Special consideration is given to the derivations of the bistatic like- and cross-polarized cross sections as well as the albedos and extinction cross sections of the irregular shaped particles (for which no analytic solutions had yet been presented).

The third group of manuscripts deals with the solution of the equation of transfer for the co-polarized and cross-polarized incoherent specific intensities (Stokes parameters) in media consisting of random distributions of irregular shaped particles

(16), (17), (20), (37). Both infrared and optical excitations are considered at normal and oblique incidence to parallel layers of particles. First order, single scatter as well as multiple scatter results are presented for particles with rough surfaces as well as particles with smooth surfaces. It is shown that the principal effect of the particle surface roughness is to make the incoherent specific intensities more isotropic, (thus smoothing out the large undulations in the specific intensities for the medium consisting of smooth particles and eliminating windows of transmission). In addition, the degree of polarization of the scattered specific intensities is significantly smaller for the particles with rough surfaces. Step by step progress on the research conducted over this period of the contract is reported in seven semiannual technical reports reproduced in this Final Report.

3. DESCRIPTION OF RESEARCH

Detailed description of the analytical and numerical techniques used in these investigations and their applications to engineering and technology are given in the reprints and preprints of the scientific manuscripts submitted with this Final Report (see list of publications, Section 6, and Appendix).

4. PERSONNEL SUPPORTED BY THIS CONTRACT

In addition to the principal investigator, Ezekiel Bahar, the main contributors to this research project are Mary Ann Fitzwater and Parveen Wahid (Post Doctoral Associates), and Swapan Chakrabarti (Graduate Research Assistant).

Mr. Swapan Chakrabarti's Ph.D. dissertation is based on the research conducted for this project. The Ph.D. thesis is submitted as an addendum to this Final Report.

5. ACKNOWLEDGMENTS

The author wishes to thank James Mink, Walter Flood, (ARO Durham, North Carolina), and Edward Stuebing and Robert Frickel (CRDC Aberdeen, Maryland), for their encouragement, suggestions and interest in these investigations.

The author also wishes to acknowledge the support he received from the University of Nebraska-Lincoln for use of its computing facilities. He is especially indebted to the National Science Foundation for the Engineering Supercomputer Grants ECS 8515794/5 he was awarded.

6. List of Publications by the Principal Investigator During Period of Army Contract
- (a) Publications in Technical Journals
 - (1) "Scattering Cross Section Modulation for Arbitrarily Oriented Composite Rough Surfaces--Full Wave Solutions," Radio Science, Vol. 18, No. 5, pp. 675-690, September-October 1983.
 - (2) "Backscatter Cross Sections for Randomly Oriented Metallic Flakes at Optical Frequencies--Full Wave Approach," Applied Optics, Vol. 23, pp. 3813-3819, December 1983.
 - (3) "Scattering Cross Sections for Particles of Irregular Shape," Proceedings of the 1982 CSL Scientific Conference on Obscuration and Aerosol Research, DRDAR-CLJ-IR, June 1983, pp. 245-254.
 - (4) "Modulation of the Scattering Cross Sections for Arbitrarily Oriented Composite Rough Surfaces--Full Wave Approach," Proceedings of the 1983 Joint International Geoscience and Remote Sensing Symposium and National Radio Science Commission F Meeting, San Francisco, California, August 31-September 2, 1983.
 - (5) "Scattering Cross Sections for Composite Rough Surface Using the Unified Full Wave Approach," IEEE Transactions on Antennas and Propagation, Vol. AP-32, No. 7, pp. 730-734, July 1984.
 - (6) "Optimum Backscatter Cross Section of the Ocean as Measured by Synthetic Aperture Radars," Proceedings of URSI Symposium on Frontiers of Remote Sensing of the Oceans and Troposphere from Air and Space Platforms, Israel, pp. 149-158, May 14-23, 1984.
 - (7) "Scattering Cross Sections by Large Finitely Conducting Spheres with Rough Surfaces Full Wave Solutions," Proceedings of the 1983 Scientific Conference on Obscuration and Aerosol Research, DRDAR-CLJ-IR, pp. 215-221, June 1984.
 - (8) "Scattering by Anisotropic Models of Composite Rough Surfaces--Full Wave Solutions," IEEE Transactions on Antennas and Propagation, Vol. AP-33, No. 1, pp. 106-112, January 1985.
 - (9) "Scattering and Depolarization by Large Conducting Spheres with Rough Surfaces," Applied Optics, Vol. 24, No. 12, p. 1820, June 1985.
 - (10) "Scattering and Depolarization by Conducting Cylinders with Rough Surfaces," Proceedings of the 1984 CRDC Scientific Conference on Obscuration and Aerosol Research, DRSMC-CLJ-IR, pp. 365-371, January 1985.
 - (11) "Like and Cross Polarized Scattering Cross Sections for Random Rough Surfaces--Theory and Experiment," Journal of the Optical Society of America Special Issue on "Wave Propagation and Scattering in Random Media," Vol. 2, No. 12, pp. 2295-2303, December 1985.

- (12) "Scattering and Depolarization by Random Rough Surfaces, Unified Full Wave Approach--An Overview," Wave Material Interaction--in press. (January 1986).
- (13) "Multiple Scattering in Media Consisting of Nonspherical Finitely Conducting Particles," Proceedings of the 1985 CRDC Scientific Conference on Obscuration and Aerosol Research--in press.
- (14) "Full Wave Solutions for Electromagnetic Scattering and Depolarization in Irregular Stratified Media," Special Issue of Radio Science on Waves in Inhomogeneous Media--in press.
- (15) "Scattering and Depolarization by Conducting Cylinders with Rough Surfaces," Applied Optics--in press.
- (16) "Multiple Scattering by Irregular Shaped Particles of Finite Conductivity at Infrared and Optical Frequencies," Radio Science--in press.
- (17) "Scattering and Depolarization of Linearly Polarized Waves with Finitely Conducting Particles of Irregular Shape," submitted for review.
- (18) "Interpretation of Backscatter Cross Sections for Normal Incidence Using Unified and Two-Scale Full Wave Analyses of Rough Surfaces," submitted for review.
- (19) "Incoherent Diffuse Scattering by Irregular Shaped Particles of Finite Conductivity," Proceedings of the International Radio Science Union Conference on Electromagnetic Theory--in press.
- (20) "Extinction Cross Sections and Albedos for Particles with Very Rough Surface," submitted for review.
- (21) "Co-Polarized and Cross-Polarized Incoherent Specific Intensities at Oblique Incidence for Particles of Irregular Shape and Finite Conductivity," submitted for review.
- (22) "Computer Aided Graphics for Three Dimensional Objects Based on Full Wave Theory," submitted for review.
- (23) "SEASAT Microwave Altimeter Measurement of the Ocean Gravity Wave Equilibrium-Range Spectral Behavior Using Full-Wave Theory," Proceedings of the 1986 International Geoscience and Remote Sensing Symposium--in press.
- (24) "Co-polarized and Cross-polarized Incoherent Diffuse Intensities Scattered by Finitely Conducting Particles of Irregular Shape," Proceedings of the 1986 International Union of Radio Science, Commission F Symposium on Wave Propagation: Remote Sensing and Communications--in press.
- (b) Abstracts and Summaries of Papers Presented at International Conferences
- (25) 1982 CSL Scientific Conference on Obscuration and Aerosol Research, Aberdeen, Maryland, June 21-25, 1982, "Scattering Cross Sections for Particles of Irregular Shape."
- (26) International Union of Radio Science (URSI) Meeting at the University of Colorado, Boulder, January 5-7, 1983, "Backscatter Cross Sections for Randomly Oriented Metallic Flakes at Optical Frequencies."

- (27) 1983 Joint International Geoscience and Remote Sensing Symposium and National Radio Science - Commission F Meeting at San Francisco, California, August 31-September 2, 1983., "Modulation of the Scattering Cross Sections by Arbitrarily Oriented Composite Rough Surfaces."
- (28) 1983 CSL Scientific Conference on Obscuration and Aerosol Research Aberdeen, Maryland, June 20-24, 1983, "Scattering Cross Sections for Large Finitely Conducting Spheres with Rough Surfaces--Full Wave Solutions."
- (29) International Union of Radio Science (URSI) Meeting at the University of Colorado, Boulder, January 11-13, 1984, "Scattering and Depolarization by Large Conducting Spheres with Very Rough Surfaces."
- (30) International Union of Radio Science (Commission F) Symposium on Frontiers of Remote Sensing of the Oceans and Troposphere from Air and Space Platforms, Israel, May 14-23, 1984, "Optimum Backscatter Cross Section of the Ocean as Measured by Synthetic Aperture Radars."
- (31) International IEEE/APS Symposium and National Radio Science Meeting, Boston, Massachusetts, June 25-29, 1984, "Scattering Cross Sections for Composite Models of Non-Gaussian Rough Surfaces for which Decorrelation Implies Statistical Independence."
- (32) 1984 CRDC Scientific Conference on Obscuration and Aerosol Research Aberdeen, Maryland, June 25-29, 1984, "Scattering and Depolarization by Very Long Finitely Conducting Cylinders with Rough Surfaces."
- (33) International Union of Radio Science Symposium on Radio Techniques in Planetary Exploration, in conjunction with the XXI General Assembly of URSI, Florence, Italy, August 26-September 6, 1984, "Scattering and Depolarization of Radio Waves by Rough Planetary Surfaces."
- (34) International IEEE/APS-Symposium and 1985 North American Radio Science Meeting, Vancouver, Canada, June 17-21, 1985, "Scattering by Anisotropic Models of Composite Rough Surfaces--Full Wave Solutions."
- (35) 1985 CRDC Scientific Conference on Obscuration and Aerosol Research, Aberdeen, Maryland, June 17-21, 1985, "Multiple Scattering in Media Consisting of Non-Spherical, Finitely Conducting Particles."
- (36) Symposium/Workshop on Multiple Scattering of Waves in Random Media and by Random Rough Surfaces," Pennsylvania State University, University Park, Pennsylvania, July 29-August 1, 1985, "Scattering and Depolarization by Random Rough Surfaces--Unified Full Wave Approach."
- (37) Schlumberger Workshop on Waves in Inhomogeneous Media, August 8-9, 1985, Ridgefield, Connecticut, "Unified Full Wave Solutions for Electromagnetic Scattering by Rough Surfaces--Comparison with Physical Optics, Geometric Optics and Perturbation Solutions Using Two-Scale Models of Rough Surfaces."

- (38) 1985 Joint Meeting of the IEEE Geoscience and Remote Sensing Society and USNC/URSI Commission, October 7-9, 1985, University of Massachusetts, Amherst, Massachusetts, "Like and Cross Polarized Cross Sections for Random Rough Surfaces--Full Wave Theory and Experiment."
- (39) International Union of Radio Science (URSI) Meeting at the University of Colorado, Boulder, Colorado, January 13-16, 1986, "Scattering and Depolarization by Conducting Cylinders with Rough Surfaces."
- (40) International Union of Radio Science (URSI) Symposium on Electromagnetic Theory, Budapest, Hungary, August 25-29, 1986, "Incoherent Diffuse Scattering by Irregular Shaped Particles of Finite Conductivity."
- (41) 1986 IEEE Antennas and Propagation/International Union of Radio Science Symposium, University of Pennsylvania, Philadelphia, Pennsylvania, June 9-13, 1986, "Interpretation of Backscatter Cross Sections for Normal Incidence Using Unified and Two-Scale Full Wave Analysis of Rough Surfaces."
- (42) 1986 International Geoscience and Remote Sensing Symposium (IGARSS'86) University of Zurich-Irchel, Switzerland, September 8-11, 1986, "SEASAT Microwave Altimeter Measurement of the Ocean Gravity-Wave Equilibrium-Range Spectral Behavior Using Full Wave Theory."
- (43) 1986 International Union of Radio Science, Commission F Symposium on Wave Propagation: Remote Sensing and Communications, University of New Hampshire, Durham, New Hampshire, July 28-August 1, 1986, "Scattering and Depolarization of Linearly Polarized Waves by Finitely Conducting Particles of Irregular Shape."
- (44) Fall 1986 Electromagnetic Wave Propagation Panel Symposium on "Terrestrial Propagation Characteristics on Modern Systems of Communications Surveillance, Guidance and Control," sponsored by Advisory Group for Aerospace Research and Development (NATO), Ottawa, Canada, September 9-12, 1986, "Scattering and Depolarization by Rough Terrain and Vegetation Covered Terrain--Unified Full Wave Approach."
- (45) 29th Midwest Symposium on Circuits and Systems, University of Nebraska-Lincoln, August 11-12, 1986, "Application of Full Wave Theory to Computer Aided Geometric Design."
- (46) 1986 CRDC Scientific Conference on Obscuration and Aerosol Research, Aberdeen, Maryland, June 23-27, 1986, "Co-Polarized and Cross-Polarized Incoherent Diffuse Specific Intensities for Linearly Polarized Excitations of Irregularly Shaped Particles."
- (47) 1986 CRDC Scientific Conference on Obscuration and Aerosol Research, Aberdeen, Maryland, June 23-27, 1986, "Extinction Cross Sections and Albedos for Particles with Very Rough Surfaces."

(c) Technical Reports

- (48) "Depolarization and Scattering of Electromagnetic Waves," U. S. Army Research Office--Research Triangle, N.C., Semi-Annual Report #1, May 15, 1982-December 31, 1982.
- (49) "Depolarization and Scattering of Electromagnetic Waves," U. S. Army Research Office--Research Triangle, N.C., Semi-Annual Report #2, January 1, 1983-June 30, 1983.
- (50) "Depolarization and Scattering of Electromagnetic Waves," U. S. Army Research Office--Research Triangle, N.C., Semi-Annual Report #3, July 1, 1983-December 31, 1983.
- (51) "Depolarization and Scattering of Electromagnetic Waves," U. S. Army Research Office--Research Triangle, N.C., Semi-Annual Report #4, January 1, 1984-June 30, 1984.
- (52) "Depolarization and Scattering of Electromagnetic Waves," U. S. Army Research Office--Research Triangle, N.C., Semi-Annual Report #5, July 1, 1984-December 31, 1984.
- (53) "Depolarization and Scattering of Electromagnetic Waves," U. S. Army Research Office--Research Triangle, N.C., Semi-Annual Report #6, January 1, 1985-June 30, 1985.
- (54) "Depolarization and Scattering of Electromagnetic Waves," U. S. Army Research Office--Research Triangle, N.C., Semi-Annual Report #7, July 1, 1985-December 31, 1985.

(d) Ph.D. Dissertation

- (55) "Scattering Cross Sections and Incoherent Specific Intensities for Particles of Irregular Shape and Finite Conductivity--Full Wave Approach," to be submitted to the Department of Electrical Engineering, University of Nebraska-Lincoln, May 1986, by S. Chakrabarti.